Report of the 20th Electron Ion Collider Detector R&D Meeting

EIC Detector Advisory Committee

March 24 – 26, 2021

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Introduction

BNL, in association with Jefferson Laboratory and the DOE Office of Nuclear Physics, has established a generic detector R&D program to address the scientific requirements for measurements at a future Electron Ion Collider (EIC). The first meeting was held at Brookhaven on May 9-10, 2011. The primary goals of this program were to develop detector technologies and detector concepts that are suited to experiments in an EIC environment, which will ensure that the full physics potential of an EIC can be harvested and that the resources for implementing these technologies are well established within the EIC user community.

The EIC Detector Advisory Committee meets twice a year, typically in January and in July. The current Committee members are: M. Demarteau (ORNL/Chair), C. Haber (LBNL), P. Križan (Ljubljana University/J. Stefan Institute), I. Shipsey (Oxford University), R. Van Berg (U. Pennsylvania), J. Va'vra (SLAC) and G. Young (BNL). Due to the Covid-19 pandemic the meeting was again held remotely by video conference and spread out over three days rather than two days. All committee members were able to attend. Normally during the January meeting progress reports are reviewed and feedback is provided to the proponents. At the July meeting both progress reports and new proposals are reviewed, and funding recommendations made. The committee would like to thank all collaborations for their excellent presentations and status reports and for their understanding for having the review held completely remotely.

This meeting was nominally the "January" meeting but given the CD-1 review for the project the meeting was deferred to March. The project has passed the CD-1 review and the mandate of this committee has come to an end. The EIC management has appointed a new Detector Advisory Committee that is integral to the project and will guide the future R&D program. For this meeting no new proposals were solicited, and this report constitutes the final report of this committee. It provides a summary of the various R&D efforts and our recommendations regarding the importance of each efforts and if it should continue to be supported under a directed R&D program or a more generic R&D program still to be defined. To help guide the incoming detector advisory committee, an appendix has been included that summarizes the timelines for the major R&D efforts.

The committee would like to thank everyone who has participated in this program over the many years for their contributions. Looking back to the May 2011 inaugural meeting of this program, we conclude that the goals that were set at the beginning of this program have been fully met and arguably have exceeded expectations. The collaborations are to be commended for their progress and achievements over the years. You brought forth a program that had a huge part in enabling the EIC. Without the work done under this program most likely the project would not be in a position to move forward so quickly. This program has amply demonstrated its significance during the writing of the Yellow Report and the related work on detector concepts. We thank you all and wish you the best of luck in the upcoming phase developing the detector proposals.

eRD1: EIC Calorimetry

Craig Woody, Carlos Muñoz-Camacho, Oleg Tsai reporting

Tungsten-fiber calorimeter development

Findings

The construction of the 6144 blocks of the sPHENIX EMCal is nearing the halfway point. These will be operated as 24,576 towers using SiPM readout. Two major sites are operating for block fabrication and one central site performs sector assembly. Congratulations to the group for demonstrating this 'at scale' production as an option for EIC calorimetry.

The eRD-1 group noted earlier that there is room for improving the uniformity of response of their W-powder SciFi EMCalorimeter. Results from FNAL test beam runs indicate that response uniformity across the W/SciFi matrix could be improved by better photo-sensor coverage. It is also known, i.e. has been measured, that PMTs well-coupled to the W-SciFi matrix give twice better energy resolution than the chosen SiPM readout. This is again presumably due to more complete and uniform light collection for the PMTs. A solution that also avoids the radial depth lost to light guides is of interest to an EIC detector barrel region, which needs to be inside the magnet coil. The team presented earlier a concept for a tiling of the readout face of an sPHENIX block (2x2 towers) using newly available 6mmx6mm SiPMs from HPK and has now obtained the needed sensors in both single and 2x2 matrix form. The current SiPMs on the back of the lightguides of the current sPHENIX towers could be replaced, or the entire light guide array could be removed and the larger SiPMs attached directly to the W/SciFi matrix. A 1-4mm thin 'light mixer' would be needed in the latter case. These SiPMs also exhibit improved noise performance compared to the (now discontinued!) series just procured for sPHENIX. An EIC detector needs an improved uniformity over that accepted for sPHENIX, and deployment of a fully 'tiled' SiPM readout presents a possible path to achieve this.

Comments

The group has built test boards to mount the larger SiPMs and showed initial results. The group showed initial results regarding transverse uniformity with two different readout schemes. If the existing sPHENIX light guides are paired with a 2x2 array of the new 6x6 mm^2 SiPMs the uniformity and light collection is improved, perhaps doubled, which helps resolution. If the light guides are replaced by a 4mm flat Lucite panel (a light mixer) and read out by a 6 x 6 array of the 6x6 mm^2 SiPMs, one sees a definite x-y structure, pointing to the need to use a thicker light mixer and/or smaller/no gaps between SiPMs. These new boards need to be designed, built, and deployed. The Committee encourages to obtain test results from this further improved configuration.

The group also examined relative behavior of W-SciFi and W-shashlik type EMCals, with a focus on covering the forward hadron-going EMCal region. This is noted further under the section on Shashlik.

Recommendation

Continue to perform tests with the large-area SiPMs, examining ways to improve uniformity. Consider other methods to improve light collection from the W-SciFi. Serve as a resource to provide known cost, schedule and personnel usage for the sPHENIX construction to EIC groups seeking to deploy a W-SciFi EMCal at EIC.

Shashlik Concept

Findings

The Committee takes note of the continued development of the shashlik calorimeter at UTFSM using W-Cu plates to realize a compact shashlik EMCal. Nine towers are now constructed and prepared for operation in a test beam; they are read out with borrowed sPHENIX electronics. The performance vis-à-vis the existing PHENIX shashlik lead-scintillator devices is predicted to be somewhat improved, yet a compelling improvement needs to be demonstrated.

The comparisons, suggested at the last meeting, to the performance of the old PHENIX shashlik lead/scintillator EMCal towers, reconfigured to read out the individual or smaller groups of the WLS fibers, are still pending, awaiting finding manpower for this effort. The group has studied this in simulations.

Simulations were used to study resolution versus sampling fraction, ranging from 1/5 X_0 to 1 X_0, with expected parametric behavior. Studies started of the existing PHENIX shashlik, which is Pb-scintillator, to see what grouping of the existing WLS fibers would help with two-photon spatial resolution, in particular discriminating two photons from one.

Comments

An improved shashlik prototype is proposed, some 12 x 12 cm^2 in size, meaning fewer boundaries and better shower containment. The sampling frequency would be reduced to ¼ or 1/5 of X_0 to approach 6%/sqrt(E) resolution. Modeling is started for WLS placement to improve light collection percentage and uniformity. Readout would be via small SiPMs, perhaps 1 x 1 mm^2, which reduces cost. These might use the smallest-available pixels from a commercial vendor to aid with radiation resistance if SiPM pixel size is shown to be a key factor.

Simulation studies for projective readouts were presented noting the importance of projective EMCal design to achieve good two-photon spatial separation. For pseudorapidities up to 1.5 or even 2 it may prove possible with an EMCal alone to separate two photons up to the 30-40 GeV range desired at the EIC, but forward of that it may be required to consider use of a pre-shower detector. Prototype studies of a physical shashlik device would be needed to learn how to make projective shashlik towers, since the usual manufacturing techniques produce rectangular grids of the sampling WLS fibers. This is a solved issue for the W-SciFi option via arrangement of the internal grids and scintillating fibers. Whether a simple machining of shashlik towers will suffice remains to be simulated and then demonstrated.

The Committee commends the progress shown, takes note of the concerns expressed about needing manpower to further this work, and looks forward to further reports. It is not clear what performance relative to the existing PHENIX shashlik is required or justified for the EIC.

Recommendation

Construct the 12 x 12 cm^2 prototype and test it. Devise a method to produce a projective shashlik tower. Continue the simulations of two-photon separation and suggest where it may be needed to employ a pre-shower detector.

Scintillating Glasses

Findings

The collaboration reported further results on making larger samples of scintillating glasses, with an initial 2x2x40 cm^3 sample prepared. This approaches 20 radiation lengths, suitable for deployment at EIC. Earlier samples have been subjected to intense gamma radiation from ^{60}Co sources and 40 MeV proton bombardment from the University of Birmingham cyclotron to check radiation tolerance. Initial encouraging results were reported for the development of grinding and polishing techniques. Efforts have started to develop good coupling to photosensors. It was reported earlier that some glasses perform well under large radiation dose, whilst other formulations were disqualified by these tests. These tests have continued and are being used to identify glasses with good radiation tolerance. Large fluorescence light yields relative to $PbWO_4$ have been noted earlier. Methods to control bubbles and localize them to the surface and tuning of glass composition to control radiation hardness and peak wavelength of light yield were demonstrated earlier. Densities above that of lead glass can be achieved, which makes these glasses of interest.

Near-term plans include measurement of light yield from cosmic-ray events and then for example from tagged photons in Hall D at JLab , which is of great interest to the Committee. Performance of these tests has been hampered by the COVID-19 pandemic; however they remain in the plan for future work.

Comments

The group obtained SBIR-Phase 2 funding for this work; congratulations! A commercial company is involved, which bodes well for large-scale deployment.

Initial in-beam tests results of a 7 radiation-length block of 2cm x 2cm transverse size with 5.2 GeV electrons were reported. The energy resolution achieved is modest, 15%, but it was a single block and thus the showers were not well-contained transversely nor longitudinally. A test with a 3x3 array of longer blocks, or a 5x5 array if possible, or with two 5x5 sets of 7-radiation-length blocks stacked longitudinally, would be of interest. The greatest interest would be for the newer 40cm long blocks, or longer blocks if they can be obtained. The simulation of these results does not quite match in-beam measurements, but it appears some adjusting of the chemical composition in the simulation is needed. This should be pursued in order to obtain a useful computational framework.

The Committee notes the crystal work on lead tungstate has concluded successfully. A new vendor is qualified, nearly 1000 blocks have been made, uniform and reproducible block production and good radiation resistance up to 1 MRad demonstrated. The cost of $15-25/cc remains an issue but deployment for very forward EMCalorimetry seems quite feasible.

A new effort on Cerenkov + Scintillating glasses has started. These start from the scintillating glasses above. These would need to be dense and also place the scintillation light above 500 nm in order to stay away from the Cerenkov light with its 1/lambda^3 dependence. A density of greater than 5 g/cc may be needed for use as a hadron calorimeter, for reasons of depth availability at EIC. A challenge will be the light absorption length if these are to be deployed as hadron calorimeters. This may offer a device resistant to neutron damage up to $10^{15}/cm^2$ fluences (1 MeV equivalent), which is of interest. The effort will need at least 3 years and has to be considered relative to other hadron-calorimeter technologies. This may be a candidate for longer-term R&D.

Recommendation

The Committee encourages continuation of this effort. The Hall D tests of the scintillating glasses are important, as are continued production of 40cm or longer samples of scintillating glass and their testing in a 5x5 array for energy resolution and shower containment.

The simulation effort for the scintillating glass should continue in order to deliver a useful framework for modelling these glasses and thus incorporating them into a detector design.

HCAL Studies

Findings

The collaboration has studied the shower containment in combined Electromagnetic and Hadronic calorimeters considered for the hadron endcap. The configurations studied included W/SciFi and Shashlik EMCalorimeters and an Fe/Scintillator sandwich design for the hadronic compartment.

Studies of e/h response for various chemical composition were studied as a function of particle energy and for several specific existing constructions.

The following two paragraphs are repeated from the last report. The available longitudinal space for this device needs to be discussed with the machine designers; the current space may be too limited. This would not be a good situation for the jet measurement program. Shifting the accelerator rings radially +-2cm with a crossing angle of 25 mrad in order to shift the IP one meter in the electron going direction would yield perhaps a meter more space (thickness) for the hadronic calorimeter, which should be given consideration, before the machine designs starts to be settled for the CD-2 baselining in 2022-2023.

The proponents should consider an HCal of at least 7 interaction lengths thickness for the jet program. It would be useful to study leakage out to 10 interaction lengths, determine where further thickness exhibits diminishing return, and discuss implications for jet measurements. These studies could formally designate the latter 3 interaction lengths as a tail catcher and study simpler constructions for its design to reduce system cost. Later studies might consider the sampling fraction of scintillator vs steel.

Comments

The parametric studies of e/h behavior versus energy and the effect on HCal resolution are highly welcome and should continue. The committee wonders if any studies of time-dependence of light from the new STAR FCAL exist? It was mentioned earlier by the group that capturing later-emitted light from neutrons might help with e/h response and thus resolution. Effort on this topic going forward is encouraged.

Recommendations

Continued support for students performing simulations is recommended. This effort needs to clarify performance with and without a tail catcher for the hadron showers, in particular as a function of pseudorapidity. A focus on chemical composition and sampling fraction would be useful. The elucidation of e/h performance should be vigorously pursued.

A test of a 60 x 60 cm^2 prototype with EMCal and HCal sections is of interest as a way of demonstrating the desired (35-50)%/sqrt(E) performance specified for hadronic calorimeters in the Yellow Report and establishing a performance baseline for cost-estimating. Whether the EMCal section could be non-used blocks from sPHENIX should be investigated. Whether the HCal compartment needs construction or recuperation of existing devices should be presented. This discussion would need to model the chemical composition for the proposed test device.

eRD6: Tracking Consortium for the EIC

Bob Azmoun and Klaus Dehmelt reporting

The eRD6 collaboration has played key roles in the preparation of the Yellow Report and is to be congratulated on their significant contributions to this reference report. The collaboration has made good progress on many fronts and is also to be congratulated on a delivering a very successful MPGD and PID research program, having brought many elements to a maturity level where it is ready to be incorporated into a TDR. Reports were given on a broad range of efforts on Micro-Pattern Gas Detectors (MPGDs) for tracking and particle identification. The status of the GEM prototypes for an End Cap Tracker was presented, as well as an update on the cylindrical μRWELL, cylindrical Micromegas and TPC for central tracking. In the area of particle identification, R&D on hybrid MPGDs for a RICH detector, with studies of new photocathodes and the development of large mirrors was presented.

Findings and Comments

The studies with the 4-GEM detector and X-ray scanner have seen significant improvement in the ability of the X-ray scanner to measure position resolutions on a par with results from a test beam. The residual distribution is a convolution of the 25 μm collimator (width), the detector intrinsic resolution, estimated to be about 40 μm, and the x-ray secondary electron range, which can be the dominant component. To establish a more point-like charge reference, they have since explored the possibility to reduce the photoelectron range by reducing the x-ray energy. By reducing the potential on the x-ray tube, they improved the resolution to be more in agreement with the beam test, which measured 55 μm resolution.

The progress with the mini-TPC prototype has been good and a direct comparison of performance of straight strips with ziz-zag readout with three different MPGD technologies was made. The position resolution vs. pitch for straight strips and zigzag shaped anodes in GEM, Micromegas and μRWELL detectors was measured in a 120 GeV proton beam at Fermilab. The conclusion is that in situations where the detector occupancy is fairly low and a relatively coarse readout segmentation is acceptable, the zigzag shaped charge collection anodes provide a very efficient means of encoding high resolution positional information, with values remaining below 65 μm for a pitch as large as 3.3 mm. The best resolution of ~54 μm was achieved for zigzag strips.

Since space charge in the drift volume is the most detrimental aspect of operating a TPC, eRD6 has correctly concentrated on ways of minimizing Ion Back Flow (IBF). In addition to these studies, the electron drift velocity, ion mobility, transverse diffusion, and the gas gain are specifications that must also meet certain criteria. CH_4 at the 10% level is desirable because it is known to be an effective "cool" gas component and falls below flammability levels. For the 2-GEM + MM option, 10% CH_4 was found to be optimal, whereas 35 - 40% performs best in the case of a 4-GEM. The collaboration has developed a hybrid MPGD option, paired with the appropriate gas mixture, capable of reducing IBF to acceptable levels and maintaining very good energy resolution and exhibits overall superior performance.

A brief status of the **cylindrical micromegas** studies at Saclay was presented with a Monte Carlo study of a hybrid design of a silicon tracker complemented by a 6-layer micromegas tracking detector. A micromegas hybrid detectors performs equally well as a TPC hybrid detector. The research plan calls for an optimization of the 2D readout patterns to achieve the design resolutions and a study to reduce the material budget even more. A small demonstrator using the ultra-light technology will be built this year with the optimized 2D readout.

Cylindrical µRWELL detectors have been further developed with a full-scale mechanical mock-up and the mechanical properties measured. The team is now working on the design and construction of a near full-scale prototype, 2m in diameter and 2m long. A hybrid design 'SIMPLE', referring to a Silicon and Micro Pattern Gaseous Detector for a Large Experiment, is now being evaluated. This is an intriguing idea where these detectors right before and after the DIRC could provide great benefit.

MPGD-style Interleaved readout, capacitively coupled to LAPPDs has been studied, which could be used for an mRICH detector to establish a high performance, compact PID RICH. At the same time, collection of the small cluster of Cherenkov photons generated in the 5mm thick quartz LAPPD window allows for a high-resolution position and TOF measurement. To accomplish this, the team proposes to read out the sensor with an interleaved anode pattern, similar in concept to ones developed for MPGDs, which effectively enhances charge sharing and delivers a resolution significantly better than pitch/sqrt(12). By doing so, significantly fewer readout channels are required, which considerably reduces the overall detector cost. The internal backplane of an LAPPD is a resistive ground plane that collects the multiplied electron signal. The collected charge is subsequently spread through this layer and induces charge onto the readout pads of an external PCB, mechanically pressed against the outer surface of the borosilicate bottom panel of the tile. This is an interesting idea, worthwhile looking at. However, one should not assume a gain of 10^7, as MCP ion feedback might get very bad at such a gain, especially if the vacuum gets worse over a period of time. One should not exceed a total charge of 2-3x10^6 to avoid these problems. Another point is that the strip readout will work only if the number of hits in an LAPPD is below a certain threshold. There is also an issue of crosstalk, ringing, and baseline restoration, which could add unwanted additional fake hits. Normally people prefer a pixel readout for RICH detectors, especially for high-rate applications. The committee suggest that the proponents determine what the noise level is in terms of the number of electrons.

The development of high resolution capacitive-sharing readout is proceeding well. A prototype with 1cm-pad readout board has been installed in beam test in Hall D at JLab, working together with the TRD group. The prototype with a 3-GEM detector worked well. Charge transfer from the top layer to the readout pads of the bottom layer preserve charge sharing information even for low-signal MIP events. Linearity, efficiency and spatial resolution were measured. The advantage of this concept is clear: one obtains an excellent spatial resolution of 190 μm for both x and y directions, while keeping the channel count low. The results are quite remarkable for 1 cm x 1 cm pad readout. However, the committee suggests the following studies: (a) the noise level in terms of number of electrons, (b) the minimum threshold required in terms of number of electrons, and (c) the minimum distance this readout concept can resolve.

Further work is continuing on capacitive-sharing readout PCBs in collaboration with the CERN PCB workshops. Two four-layer boards are being investigated. One has 9 mm x 9 mm pads and one has X&Y strips with 800 μm pitch. This PCB will allow the study of the impact of the inter-pad gap on the spatial resolution performance of the capacitive-sharing readout concept.

The GEM End Cap Tracker has rebuilt their detector using new PEEK inner frames; once the frames were released from the optical table, shorts appeared, which are attributed to the material and deformations of the carbon fiber frames. The deformation analyses show that the addition of one central rib to the frames and the use of thicker, professionally manufactured quasi-isotropic carbon fiber material should result in an assembly that will allow proper stretching of the foils in the prototype. The design for the carbon fiber frames with ribs will be completed and two such frames will be produced from the commercial carbon fiber plates that is already procured. It seems that the proposed two ribs in the middle will not be sufficient.

There are several efforts aimed at the development of **hadron identification at high momentum** at an EIC. At INFN Trieste, MPGD sensors for single photons are being studied. A portable gas mixing system was developed for well-controlled and reproducible measurements of the effective Quantum Efficiency (QE) in different gas atmospheres. Twenty new thick-GEMs have been produced by industry and submitted to the refinement protocol in Trieste. No raw pulse shapes were shown, and the committee wonders how the circuit is performing. It was noted that the absence of a resistive layer on top of the anode electrodes is limiting the degradation of the dE/dx information in the collected signals. The mechanism for this is not understood. The advantage of a thick GEM compared to a regular GEM was not explained. The Kapton material seems much more compatible with very high purity requirements to operate a photocathode at 140 nm compared to G-10 material, even if it was baked. It seems to us that a Thick-GEM is more compatible with a CsI photocathode than with a Diamond-based photocathode.

The work on the development of Photocathode Materials at INFN Trieste is ongoing. Last time the committee recommended that the PID-MPGD efforts be more quantitative with respect to the requirements for the EIC physics program and compare the current efforts on diamond photocathode development with, for example, CsI. Variables we are interested in are the number of detected photoelectrons per ring, Cherenkov angle resolution and projected PID performance in terms of number of sigmas as a function of momentum. No simulation results, in terms of number of Cherenkov hits and Cherenkov angle resolution, were mentioned in the report.

Recommendations

The team is to be congratulated for nearing completion of the GEM R&D for end-cap tracking. Completion of these studies under a targeted R&D program is strongly supported.

The efforts to complete studies on Ion Back Flow (IBF) versus resolution with different avalanche schemes and operating gases is far advanced. Completion of this R&D under a directed R&D program is also strongly supported. Studies of the MM+2-GEM detector to the static bi-polar gating grid in a strong magnetic field are also encouraged.

The development of cylindrical µRWELL detectors in a hybrid configuration, where µRWELL detectors right before and after the DIRC could provide great benefit, is an interesting idea and supported under a generic detector R&D program. The collaboration is encouraged to narrow the number of options it wants to pursue and decide which elements should receive emphasis for directed R&D to be completed by the time of writing a TDR. The µRWELL technology could be part of the directed R&D program if the team or collaboration makes it a priority.

The use of LAPPD for mRICH is an interesting idea, worthwhile to study. Usually, RICH detector designs prefer to use a pixilated readout. The strip readout will work only if the number of hits in an LAPPD is below a certain threshold, and this threshold should be understood. We believe that one should not assume a gain of 10^7, as MCP ion feedback might get very bad at such a large gain, especially if the vacuum gets somewhat worse over a period of time. One should not exceed a total charge of 2-3x10^6 per hit to avoid these problems and have a stable operation. There is also an issue of crosstalk, ringing and baseline restoration issues, which should be studied.

Characterization of capacitance-pad-readout for the μRwell technology is worth pursuing as generic detector R&D. These studies should become more quantitative. The μRWELL detector development in general is interesting and further R&D is encouraged under a generic detector R&D program. The consortium should compare the various choices of technology for different subdetectors in an EIC detector and quantify and validate the choice through simulations and mechanical mockups.

The development of new photocathodes is promising, but on a longer timescale than the call for detectors. This generic R&D is strongly encouraged.

The study of meta-materials was not presented. However, continuing studies of meta-materials is strongly encouraged under a generic detector R&D program.

eRD14: Integrated Particle Identification for a Future EIC

Jochen Schwiening, Xiaochun He, Marco Contalbrigo and Gary Varner reporting

The eRD14 collaboration is making progress towards the realization of particle identification for the EIC. The progress over the past years has been remarkable. Nevertheless, several issues have to be resolved before the CDRs can be submitted. The committee makes the following observations based on the report and presentations.

Findings and Comments

dRICH:

The dRICH group has finished MC studies of the performance of a dual-radiator (aerogel+gas) focusing RICH, indicating that it will fulfil its aims, a reliable pi/K separation up to 60 GeV/c.

The group is preparing a concept prototype for the test beam, components are under procurement, test is scheduled for October 2021 at CERN. In the beam test, MaPMTs will be used as a reference detector for conceptual studies, and an array of SiPMs will be studied as the candidate for the final photo-sensor.

The group has a program to investigate the operation of SiPMs in the radiation harsh environment and for mitigation methods for the consequences of the radiation damage by employing low temperature operation combined with occasional high-temperature annealing. The related engineering challenges require further studies.

For the coming years, the following items will be studies/developed: aerogel performance and handling, gas handling and alternatives to greenhouse gases, production and handling of mirrors, lightweight mechanical structures. Considerable effort will be devoted to the studies of the read-out electronics candidates.

mRICH:

The mRICH, a lens-based, compact, and modular Aerogel RICH, is designed to provide pion/kaon identification with momentum coverage from 3 GeV/c to 10 GeV/c and e/π separation at lower momenta below 2 GeV/c.

In spite of promising initial results, including an early beam test without a tracking system, the full performance is yet to be demonstrated in the test beam. Two photosensor types are being considered, SiPMs and LAPPDs. In the beam test, they plan to employ an LAPPD sensor with a pixelated (4-5mm) readout. Such a beam test is in preparation with the eRD22 proponents at JLAB in Hall D, which has been delayed because of the pandemics.

The committee has not seen a demonstration of the expected Cherenkov angle resolution for tracks that are off-axis or inclined versus the mRICH module.

hpDIRC:

The aim of this effort is to develop a very compact barrel EIC PID detector with momentum coverage reaching 6 GeV/c for π/K, pushing the performance well beyond the state-of-the-art for DIRC counters.

Beam test data shows excellent agreement between the measured and simulated data for two main parameters defining DIRC performance, the photon yield and single-photon Cherenkov angle resolution.

A permanent cosmic ray test stand for prototype testing is in preparation at SBU, and is waiting for the PANDA prototype to clear the administrative hurdles.

The simulation study of the potential contribution of the hpDIRC to the e/π identification at lower momentum shows that the hpDIRC provides e/π separation at the level of at least 3 sigma at a momentum of 1.2 GeV/c, which is at the upper limit of the range where supplementary identification of the scattered electrons is most important.

Photosensors: the various types of MCP PMTs seem to be compatible with a 2T field, but not with 3T; a detailed field map in the region to be occupied by the sensors is needed. SiPMs are a possible alternative but cooling them to -30C as discussed for mRICH and dRICH, would present a challenge in this case where sensors are in contact with the quartz body.

The DIRC group has performed radiation hardness tests of various material candidates for a lens. To test the prototype radiation-hard lenses with a high refractive index, a laser system is currently being commissioned and calibrated. The new prototype lenses (PbF2, sapphire) were delivered and are ready to be tested. A Geant simulation of this setup was developed to study in detail how well Geant4 reproduces optical aberrations. The laser setup will allow to study optical aberrations and compare the measurements with the Geant4 simulation.

The proponents are also discussing an interesting option of recycling the BaBar DIRC bars to save production cost and avoid potential delivery uncertainties that have been encountered in similar systems (BaBar, Belle II). The option is not without technical challenges (disassembly, cutting the bars, optical quality after the procedure). The committee notes that this option has to be explored very soon because of the expected phasing out of the available expertise at SLAC. The time schedule for the hpDIRC, as given by the collaboration, is given in the appendix. We note that items related to bar box disassembly, bar cleaning and bar QC are included, but nothing is listed to put it together again into final new bar boxes. To make new bar boxes can take easily another half a year or longer. We note that a new clean room will have to be erected and attention for cleanliness will be essential.

MCP tests in magnetic field:

Tests of high magnetic field operation are being continued with several Planacon and Photek samples at JLAB. Gen-II LAPPDs and ANL MCP PMTs will be tested at a beam test at FNAL in May. A highly pixelized LAPPD version is under preparation. It is not clear if any of them are compatible with 3T operation.

Electronics:

The committee sees good progress in the area of electronics. This electronics development is essential at this point to evaluate various RICH detector concepts in test beams and on test benches.

Recently, an SBIR proposal "Application Specific High Fluence Anode Design" led by Incom, Inc. in collaboration with Nalu, BNL, and ANL was approved to further optimize the capacitively-coupled LAPPD and its readout electronics.

Lessons learned from the SiREAD ASIC are being applied to a next-generation HDSoC 32-channel SiREAD ASIC. They specifications call for a sampling rate of 1-2 GSa/s, analog bandwidth of~0.5GHz, power consumption of 20-40 mW/channel. Unless the amplifier will be slowed down further, one can end up with some pulses having just one sample on the leading edge, which is not good for timing; Belle-II TOP DIRC has two samples on the leading edge.

Following a recommendation from the EIC R&D committee, an initiative has started to investigate the alternative use of a time-over-threshold (ToT) discriminating readout for the PID detectors at the EIC. There is an effort to perform initial studies of the alternative ToT readout architecture based on the ALCOR ASIC. A prototype ALCOR chip was produced; functionality tests have been initiated and have so far provided encouraging results. The design of a complete readout chain based on the ALCOR chip is in progress. The initial target is to support the SiPM irradiation tests. It would be interesting to understand how the ALCOR chip compares with the TOPFET2 chip, which is used in the TORCH and Endcap Panda DIRC detectors. For comparison, the TOPFET2 ASIC has less than ~10mW/ch., no amplifier, and an average TTS resolution of ~70ps.

Recommendation

The consortium was formed to make the multiple R&D efforts more coherent and amplify the progress, while reducing duplication. Although there is remarkable progress in most areas, considerable effort remains before a CDR can be submitted.

Specifically, the following should be developed:

1. dRICH should define the tests with irradiated SiPMTs more clearly.
2. mRICH should demonstrate that its focusing concept does produce expected Cherenkov angle resolution for arbitrary track direction.
3. MC simulations should be performed for an mRICH coupled to an LAPPD with the anticipated readout pattern, to see if it will perform sufficiently well.
4. We support the present design of a cosmic ray telescope. Its operation will depend how successful it will be to remove cosmic ray showers containing soft tracks. To use LAPPD detector from the start seems like a good choice since it has a large footprint.
5. hpDIRC should present a clear solution for a detector choice if the magnet operates at 3T.

eRD17: Beagle

M. Baker reporting

BeAGLE is the most fully developed of the e+A generators for physics at the EIC, providing predictions for the hadron/ion final state as well as the lepton/photon induced vertex. The committee has observed the evolution of BeAGLE over the last few years. We have been impressed by the team's rate of progress and their responsiveness to the needs of potential users. As such BeAGLE has been indispensable to the development of informed decisions about detector design at the EIC, as evidenced by its use in the Yellow Report.

Findings

We have been impressed by the flexibility of the team to the changing situation in two respects in particular:

(i) Whereas the team had intended to install RAPGAP in the program, they have recognised higher priorities of the community in identifying benchmark processes to be implemented and they have completed the work on three such processes for the Yellow Report. This effort involved the further development of one of their original goals of tuning BeAGLE to E665 data;

(ii) The team has achieved this despite the Covid 19 pandemic requiring less efficient remote working with their Chinese collaborators.

Comments

There are four main goals for the remainder of FY2021. The immediate technical goal is to implement the Short-Range Correlations (SRCs) in DIS events using the Generalised Contact Formalism (GCF)+BeAGLE. The second and third goals guarantee the legacy of eRD17 as the team is now ensuring that the code can be used by general users rather than only the developers, and is providing documentation including reference publications, crucially providing example control files for common processes and specifying the preferred BeAGLE tune. Finally, they will support the ongoing efforts to study specific detector designs and the design of the 2nd IR.

Recommendation

In summary BeAGLE has had a very good track record of delivering on its goals, and its goals have been integral to the EIC detector design. The committee believe it is vital that the *development,* as well as the use, of BeAGLE continues beyond FY2021. Accordingly, a mechanism needs to be identified for the labs or community to support targeted BeAGLE development.

Subatomic matter is unique. Interactions and structure are entangled because of gluon self-interaction. The EIC is needed to explore the gluon dominated region, while JLAB 12 is needed to explore the valence quark region. BeAGLE has a role to play in both. We list examples here:

> Comparing and tuning the GCF+BeAGLE-INC process to JLAB12 and other SRC data, which will become available copiously in the next few years, will be valuable for the JLAB12 physics program as well as validating the BeAGLE intranuclear cascade.

Improving the description of multinucleon shadowing and/or parton saturation in BeAGLE. There is no general-purpose code which addresses this physics.

Improving the handling of "Fermi-motion" in the non-SRC part of the spectrum. Currently, the cross-section for at-rest nucleons in the nucleus is used and then the 4-momentum to the final products to put the Fermi-motion of the struck nucleon in is done by hand. In principle, one should pick the struck nucleon momentum and initialize Pythia with that to get the right cross-section. We are not aware of any general-purpose code that does this correctly at present.

Improving the light ion handling in BeAGLE. Currently BeAGLE works reasonably well for p,n,d and then also A>=12. A=3 and 4 and even 5-11 are questionable. The theoretical progress and interest in these nuclei are significant.

One piece of eA physics which is completely missing now, but where experimental and theoretical results are expected over the next few years is 3-body short-range correlations. The EIC is fairly unique in being able to more fully reconstruct the nuclear final state so it will be good physics to attack. The BeAGLE work just completed using GCF+BeAGLE should allow the team to simulate the background: 2-body SRC w/ nuclear breakup faking a 3rd body. But when the 3-body version of GCF is available it makes sense to study the EIC's ability to measure that signal by combining that new code with BeAGLE.

The third of three bullets in the section of the yellow report called “The Nucleus: a Laboratory for QCD” is: Particle propagation through matter and transport properties of nuclei. BeAGLE has a package "PyQM" which is designed to simulate parton propagation through matter. Upgrading this is a potentially very important path to explore.

The role of BeAGLE in future EIC detector upgrades is also important. There are two types of upgrade to consider:

i) Technology driven upgrades - where the target physics in known, and the community seek an improved detector to address it. Here BeAGLE plays a crucial role in the detector optimization, but BeAGLE development is not needed.

ii) Physics-discovery-driven upgrades - where new discoveries in e+A or e+p or p+A theory or experiment occur. Adding such processes to BeAGLE is crucial to gauge how performant the current (FY21) detector design is for these new processes and to consider ways to improve the detector. Clearly, specificity awaits the discoveries, but they are almost guaranteed given the pace of the field.

eRD21: Background Studies

Charles Hyde reporting

Findings

The eRD21 team has made excellent progress since our last report and the team should be congratulated on the contributions they made to the background studies reported in the EIC Yellow Report and CDR.

Highlights include near completion of the residual-gas background study using FLUKA. The simulation is based on a thin "wire" of artificially inflated pressure rather than cross-section reweighting. Checks of the linearity of the electromagnetic and neutron energy spectra appear reasonable for pressures over two orders of magnitude, from 0.1 mbar to 1.0 mbar, although a comparison is not made with the 100 mbar pressure of figure 10.16 of the recently published EIC CDR. (We note that the scale factor of 6.25×10^8 quoted in this report appears incorrect. It was subsequently confirmed with the eRD21 team that this was a transcription error only, and the rates in Table 1 are correct. The scale factor should be 6.25×10^9 – it was corrected in the presentation). If the latest checks are considered sufficient to validate extrapolation of the spectra down to 10^{-9} mbar, then the predicted maximum yearly neutron fluence of around 10^{11} n/ cm^2/ year is well within the 10^{14} radiation tolerance.

We requested in our last report that a comparison with a GEANT4 model is important to pursue, however, the programming overhead was considered beyond the funded scope. For future studies, please note that the existing model might be easily ported into the GEANT4 based Beam Delivery Simulation (BDSIM) accelerator code, which already offers cross-section upscaling for beam-gas studies, incorporates easily configurable accelerator lattice optics and full particle tracking.

The beam - gas simulation indicates that the neutron flux at some locations exceeds SiPM tolerance. Both the electron beam and proton (ion) beam can produce neutrons. Do the simulations follow neutrons until they thermalize? The committee notes that for the electron beam, radiative Bhabhas, which are created in bends, may strike the beampipe producing showers resulting in neutrons. We understand that the synchrotron radiation simulation includes photons generated in the last bend (about 30 m upstream) and the two quads in between that bend and the IP. We recognize the annular masks now introduced in the simulation will ameliorate their impact and this was demonstrated in the presentation where the energy deposition in the SVT falls by a factor 3.4. The committee is encouraged by this.

A new study of beam-beam e-p interactions was launched to determine the dose rates from hadronic cascades reaching the zero-degree calorimeter (ZDC). After identifying and correcting some external issues with the FLUKA simulation, the peak equivalent neutron flux from e-p collisions is shown to be an order of magnitude less than from residual-gas interactions.

The dominant source of backgrounds is therefore predicted to be from synchrotron radiation and impressive progress has been made in updating the SyncBkg and GEANT4 models with the evolving lattice, the e-beam emittance including halo, and multiple geometry updates. The simulations in the report indicated the SR background of hits in the SVT to be unacceptable. However, this was updated in the presentation; the study now includes an annular photon absorber (a 2cm inner radius constriction of the beam pipe) that reduces the dose by factor of 3.4. To do this, the beampipe, including the annular mask was directly converted from the EIC Project CAD files. A further reduction came from an erroneous numerical factor: the occupancies were overstated by the number of staves per layer. Occupancies are now predicted to be a few tenths of a percent. It will be important to use a current SVT geometry file in further simulation studies and liaise closely with e.g. eRD25 to ensure the levels of occupancy produced with suitable shielding strategies are consistent with the recommended values for operation of the sensors.

A further reduction in predicted occupancy is expected from modelling a thin Au coating on the Be chamber which is planned to be implemented in the remaining project time along with a comparison with SYNRAD code from CERN.

Comments

The eRD21 project is comprehensive, it includes the studies of beam-gas background simulations, beam-beam simulations and synchrotron radiation (SR) with simulations of equivalent neutron flux. The eRD21 team developed the necessary tools to implement an accurate beam-pipe geometry based on a CAD model of the engineering design. Going forward they have the potential to provide both dose values, and detector occupancy from the beam-gas interactions and SR, including energy and particle-type of all secondaries.

For synchrotron radiation the eRD21 GEANT4 treatment is more detailed (in re-scattering effects) than SYNRAD. The eRD21 team proposes to examine backscattering of synchrotron photons from the downstream beampipe and window at the end of the 0-degree beamline. For this the GEANT4 approach is more suited than SYNRAD.

The eRD21 team includes simulation experts working closely with the mechanical and vacuum engineers as well as with nuclear and accelerator physicists. They are well positioned to work closely with the Project team in the preparation of the detector design as the Project moves from conceptual design to technical design in preparation of the Project Critical Decision–2.

eRD21 could also support the EIC user community's detector design efforts with tailored background simulations of specific detector proposals which are critical for beamline refinement and technology choices of any detector design.

Recommendation

As we noted in our last report the EIC has three working groups studying backgrounds: the EIC project IR working group; a new working group for a second IR that has different sqrt(s) vs. luminosity dependencies; and a synchrotron radiation task force which includes Machine & Experiment experts from JLab and BNL. It is crucial that eRD21 work closely with these groups going forward. Furthermore, it is recommended that the software developed by this eRD collaboration be actively shared with the community.

eRD22: GEM-based Transition Radiation Detector

Yulia Furletova reporting

Findings

The TRD group has made very good progress over the past few years. The identification of secondary electrons is important for EIC physics. It is critical for the project to determine the pion rejection factor at a level of 10-100.

So far, the group has used 3-6 GeV electrons at Jefferson Lab (Hall-D) and also hadrons coming from target collisions. For example, pions, coming from the decays of rho-mesons, were identified by the GLUEX DIRC. They used likelihood and artificial neural network (ANN) algorithms to determine the electron identification efficiency and pion rejection power. Electron/pion rejection factor of 9 and an increased electron response of a factor 3-4 has been achieved with radiator compared to without radiator, both in good agreement with the MC predictions. This test was carried out in the summer of 2020 with special precautions against covid-19, which is a great achievement.

The group used a small 10cm x 10cm triple-GEM prototype with a drift distance of ~2 cm, a 10cm thick fleece radiator, and Xenon-based gas. The test initially used the COMPASS experiment X & Y strip readout with a pitch size of 400 μm. While this is optimal for a high occupancy environment, the large number of channels does increase the price of the readout electronics. Therefore, in collaboration with eRD6, work is under way to develop a novel anode readout low channel count capacitive-sharing readout PCB. This novel capacitive-sharing readout PCB combines three crucial advantages: large readout pads or strips to reduce the number of readout channels, excellent spatial resolution (despite the large pad size) and improved noise reduction. Preliminary results of the test beam data of the large pad capacitive-sharing readout indicate that a spatial resolution of ~200 μm could be achieved.

Comments

The group has seen nice accomplishments in several areas. An electron/pion rejection of 9 has been measured and an electron response with & without radiator of 3-4, both in good agreement with the MC predictions. Work was done with a small 10cm x 10cm triple-GEM prototype with a drift distance of about 2 cm, a 10cm thick fleece radiator, and Xenon-based gas, using a novel anode readout low channel count capacitive-sharing readout PCB. Preliminary results of the test beam data of the large pad capacitive-sharing readout indicate that a spatial resolution of ~200 mm could be achieved. The team concluded that they really cannot slow down the sampling speed significantly compared to fADC125. For example, 80ns shaping time, provided by the SAMPA V5 chip, is too slow.

The future plans of the collaboration include:

1. Beam test at Fermilab to measure the pion rejection factor.
2. Test of different material types for radiators.
3. Design of a recirculation gas system, including a recovery for Xenon.
4. Work on more sophisticated algorithms for real-time data processing.
5. Development of a large-scale prototype.

Recommendations:

1. Measure the rate and multiple-hit capability of the new capacitive-sharing readout PCB. Higher rates may lead to problems related to resolving two close pulses in the presence of possible pulse ringing, baseline shifts, and crosstalk. For example, one can take some beam test data while exposing the detector in parallel to a random noise from a Xenon lamp. If one wants to do hard cuts on data at FPGA level, one should start learning soon. This should be understood before real-time data processing.
2. Start preparing for a 2-meter GEM sector prototype soon under the directed R&D program
3. Study the performance of real time processing in high-rate operation.

eRD23: Streaming Readout

J. Bernauer reporting

Findings

The collaboration has continued to hold meetings and workshops (the latest last November) to good effect. The collaboration argues that presently available technology for streaming readout (SRO) can handle the data transmission and storage problems inherent in a streaming readout for an EIC detector. They also acknowledge that the real limitations in such schemes come from the cost of storing data. For instance, the presentation mentions that sPHENIX is doing streaming tests at 18Tb/s. Saving that much data (about 20,000,000 TB per accelerator year) would cost order $1B in disk per annum – unlikely given ONP's present operations budget.

In the proposal, but not so much in the presentation, the proponents acknowledge that different types or levels of triggers / filters / feature finders / reconstruction may be applicable for different sub-detectors.

Comments

The proponents point out, quite reasonably, that detector readout cannot be an "afterthought" but must be included in the detector TDR. However, the proponents seem to be under the impression that a new ASIC for some sub-detector would need many years of development. Specification of or understanding the requirements for some new ASIC could indeed take a good deal of time but implementing a solution to those requirements should not take a long time if those requirements are technically feasible.

The presentation focuses on "integrating SRO into detector design". This may not be the correct focus since the challenge is not, as the collaboration points out, to just move data but to filter that data down to a size that could actually be stored.

Recommendation

The committee recommends that the collaboration concentrate future efforts on understanding on how to reduce the size of the data stream so that an EIC detector could actually afford to store the resultant stream. What combination of hardware triggers, firmware feature extraction, software feature extraction, low level reconstruction, data compression or other schemes could reduce the data volume to a manageable size. It seems likely that it will turn out to be optimal to use different strategies for different sub-detectors and different data streams.

eRD24: Roman Pots

Alexander Jentsch reporting

Findings

The collaboration has continued and expanded their simulation work to arrive at a baseline description of the spatial and temporal resolution requirements for an EIC detector to adequately cover the physics requirements across the energy scale. The resultant 0.5mm pixel size and 30-50ps timing goals have been turned into an initial conceptual design for possible detectors – two layers each in two separate Roman Pots about 2m apart along the beam line.

The preliminary detector design allows an initial estimate of the readout details including power needs. Using the ALTIROC chip, used in the ATLAS timing layer as a model, but increasing the channel density to allow for smaller pixel sizes, gives a total power estimate for the two Roman Pot installations of about 1.5 kW or about 1W/cm^2. A plausible design is beginning to emerge with a clear goal for the collaboration to be ready for an early TDR.

Additional work has been done on producing new sensors at BNL – especially AC coupled sensors – and measuring candidate LGAD sensors at BNL, UCSC and FNAL with betas, lasers and with a test beam. The results are encouraging. The collaboration has also done bench tests using the ALTIROC to successfully read out an AC-coupled LGAD sensor and is starting to explore how to modify the ALTIROC design to be better suited for EIC use.

The collaboration presented a preliminary cost estimate for the production of a Roman Pot system that is modeled on and scaled from the fairly well-known ATLAS timing layer costs. This should provide a good standard against which to test a bottom-up estimate in time for a TDR.

The collaboration has made an explicit effort to expand its base and a much larger consortium of capable institutions is forming to address the construction of an actual detector. This new consortium has already met twice and seems likely to be able to grow into an integral part of a future EIC detector collaboration.

Comments

The committee commends the collaboration for significant progress in the past year. In general, the collaboration (and now the new consortium) seems to be on a good track for producing a successful sub-detector system in time for the EIC commissioning.

The committee is, however, a bit worried by the preliminary estimates of required power density – this is not a trivial amount of power to handle in a small space with many very stringent constraints in terms of stability, sensitivity and mass.

The committee is pleased that the collaboration has begun to discuss timing with the accelerator division, but is worried that, as of yet, no work has been done to address the difficulties of getting pico-second level references from the central accelerator complex to the location of the Roman Pots. A test beam measurement of time to some tens of picoseconds is not a system level demonstration of such timing precision. Not only is there dispersion in the kilometer scale cables carrying any timing signals, there is change in cable electrical length with temperature and other stresses. This coupled with a signal from the LGAD that may have a peaking time in the range of 5ns makes stable 30 ps timing extremely challenging. The committee also notes that the ATLAS timing layer TDR goes into a good deal of detail worrying about short and long-term corrections for temperature variations at the module level (a small part of one endcap disk) but points out that non-minimum bias events produce a largish number of hits in the timing layer as well as associated low-eta hits in the barrel so that even event by event timing corrections are possible from the data itself. While the EIC's forward Roman Pots benefit greatly, relative to the LHC case, by very low event rates and track counts, they are, by the same measure, not able to take the same advantage of event data to correct timing errors. This is not an easy problem.

Recommendations

The committee recommends that as the detailed mechanical design of the Roman Pots advances that those designers work closely with their accelerator counterparts to ensure that all of the constraints and requirements imposed on that space can be satisfied while still preserving the desired physics performance. This seems especially true in terms of the power that needs to be dissipated in the readout system as it affects local mass concentrations or changes in stress and location of the beam pipe with the detector powered but there will be almost certainly a number of additional items needing careful consideration that will be discovered during the design process.

The committee recommends that the collaboration should consider developing a crude baseline design of how system timing could work in practice and examine how to test the assumptions made in such a design. For instance, is a time over threshold measurement sufficient to adequately correct the time walk of a pulse with a 5 ns peaking time? Can a km scale cable from the accelerator complex to the IR either be held at sufficiently constant temperature or can the effective length be compensated using temperature measurements? What type of cable (coax, optical, STP, …) can produce sufficiently low jitter over the expected length?

eRD25: Silicon Tracking

Laura Gonella reporting

The Committee thanks eRD25 for a clear, well-organized, and comprehensive presentation and report. The Committee acknowledges the great progress made on building this consortium out of the earlier individual efforts and the further work now to form a larger and broader EIC Silicon Consortium. The Committee is also very aware of the extremely short timescales shown, at the overall EIC project level, for the critical decision process, with CD2 in the very near future. The Committee's recommendations are, to some extent, influenced by this.

Findings

The collaboration has focused in four areas. They have joined with the ALICE ITS3 R&D program on MAPS towards acquiring a sensor for the EIC detector in 65 nm technology. They have pursued an active simulation and performance effort aimed at evaluating all-silicon and silicon hybrid tracker solutions. They have studied issues around services and powering. They are developing a wider EIC Silicon Consortium towards a full tracker project.

The team is working closely with ALICE colleagues on the development of readout in the 65 nm process. The team also retains the 160 nm technology as a fallback/backup potential. Going forward there are efforts planned both on sensor testing (MLR1 submission) and on the development of the larger stitched structures (MLR2 submission). In parallel, services design, refined power budgets, and alternative powering architectures are being studied.

The simulation effort has reached a level of maturity such as to provide the two baseline tracking concepts in the recent Yellow Report. Performance comparisons between the all-silicon and hybrid silicon layouts were shown.

Good progress was noted in the formation and growth of the EIC Silicon Consortium. An EOI was submitted. New groups are stepping up as well. Regular meetings are underway, and tasks and work packages are being defined. In particular much effort is being organized, and logistical aspects are being addressed, around the IC technology access for additional groups.

Comments

The EIC and ALICE ITS3 efforts diverge, somewhat, in the stave specific version of the sensor which will be stitched in some EIC specific way. We are impressed that the stave specific sensor appears to be an easier problem than the large sensor. Nonetheless there can still be integration level surprises. With the short timescale risks must be understood vis-à-vis, for example, the need for multiple IC runs to work out bugs.

The Committee is also concerned about the process and timeline for making an alternative powering technology selection – serial vs DC-DC. We think the serial case was presented with excess pessimism. In other efforts the time to design and debug alternative powering systems was significantly greater than expected. In the case of DC-DC there are also custom IC bottlenecks which present additional risks, which were realized in other projects.

Recommendations

The team should monitor carefully the evolution of the 65 nm design and fabrication process. In particular, understand where and when the EIC specific breakpoints occur and to be aware of any risks associated with that. In this regard, continue to consider carefully the risk/benefit in the case of the 160 nm fallback. Should that effort be elevated?

Considering our comments on serial vs DC-DC powering the Committee recommends that the project carefully reevaluate the time, effort, and technical issues around serial powering and certainly not dismiss it out of hand. Look carefully at the custom components which have already been developed by the HL-LHC projects and determine whether any of these could be carried over, in either the serial, or the DC-DC case, to the EIC project.

eRD26: Compton Polarimetry

Ciprian Gal reporting

Findings

The authors are focused on building first a 10 mW system that demonstrates the needed laser intensity and time structure including repetition rate, short pulse duration, and fast rise/fall time. Acquisition of a laser diode, fast pulser, YDFA fiber amplifier with 20 dB gain, and ancillary fiber-coupling and diagnostic equipment is now started. This needs to be assembled and performance demonstrated.

Comments

The authors note that moving the polarimeter location from IP12 to IP6 means a mixed polarization state of L and T will exist, in particular at 18 GeV where roughly 70% each is expected. This increases the demands on the precision of the measurement due to reduced asymmetry in any given mode. The authors presented tables illustrating this. For a future proposal, the authors should work back to the corresponding demands on laser power and measurement time and show they are consistent with proposed EIC electron refill times.

The authors note the intense flux of synchrotron radiation photons near their proposed electron detector. Simulations to study this and the background it produces via interaction with the beampipe wall, and resulting rates at their proposed detector location, have started. For future presentations it will be important to quantify those rates, convert them to hits/second in a proposed segmented detector, and suggest existence proofs for such a detector or a plan to realize one. It would also be useful to exhibit the expected energy spectrum for both scattered synchrotron photons as well as for the Compton-scattered photons that are to be measured, perhaps shown as photons/second vs measured energy.

Recommendations

The laser system needs to be assembled and operated and results reported. The proposed scheme for increasing power and doubling the frequency (e.g. via a crystal) should be presented. The simulations of background should be pursued with great vigor. A schema for a readout technology should be sketched out

The Committee asks if this is not an appropriate project for R&D supported from the accelerator side, with construction similarly supported. The polarimetry is clearly a key component of the EIC.

eRD27: High Resolution Zero Degree Calorimetry

Michael Murray reporting

Findings

A high-resolution, position-sensitive Zero Degree Calorimeter (ZDC) is being developed to measure neutrons and photons at the EIC, with a strong physics case. The requirements to access this physics program is a calorimeter at very small angles to detect photons below 300 MeV and fully measure the energy of neutrons up to 100 GeV.

Comments

A total absorption calorimeter is needed with about 1cm position resolution and 50%/√E hadronic energy resolution. It will require a well-segmented EM compartment with good energy resolution to isolate and veto the soft photons. To veto photons up to 400 MeV, 5-6cm of $PbWO_4$ EM calorimeter seems an adequate choice; the expected load of 6 10^{11} n/year seems tolerable for $PbWO_4$.

Following a recommendation at the July 2020 review, the rate capability of the device has not yet been fully addressed; it is expected that luminosity-dependent calibration corrections will be needed to mitigate the effect.

A strong collaboration with the accelerator team is needed to integrate the detector, and the proponents are well aware of it, profiting from the experience in integration of ZDCs at LHC. The team is encouraged to develop in more detail, in collaboration with the accelerator team, where in the accelerator lattice the ZDC would fit and what are potential apertures, e.g. in the lattice magnets, that the ZDC might exploit for its acceptance.

Recommendation

The committee strongly supports this project, since it will enable unique physics.

eRD28: Superconducting Nanowire Detectors for the Electron Ion Collider

Tomas Polakovic reporting

Findings

The superconducting nanowire technology is a new exciting technology with potentially great results and should be definitely supported. There is rapidly expanding interest in this technique.

Although these devices are known for about 20 years, they are novel in the high energy/nuclear physics field.

The team has seen some nice accomplishments to date:

1. Finished groundwork necessary for testing and fabrication of these detectors and started to produce the first practical pixel designs.
2. Simulations of energy deposition in nanowire and their response to particle crossing.
3. Built a portable cryostat compatible with vacuum systems of accelerator beam pipes capable of 3 K operation independently of the accelerator system cooling.
4. Good performance as single-photon counters in magnetic fields up to 5 T.
5. Detection of 400 nm photons using LED, with less than 1 dark count per second.
6. Proponents exposed the detector to ATLAS neutron background near beam dump for a month with no severe deterioration.

Comments

To bring this technology to a level of maturity to be considered for a CDR, multiple areas need more work. For example, it needs to be demonstrated that these detectors work for detection of particles in test beam. A good timing resolution of ~20 ps needs to be achieved. The front-end electronics needs further design. At present, a low-power ASIC does not exist, and the proponents plan to work with ASIC designers to develop a custom ASIC for readout for these devices. Also, a practical detector geometry needs to be designed.

Recommendations

We strongly encourage continued support of this effort under the generic detector R&D program. A test beam effort should be pursued with priority and results from that beam test should be obtained and shared with the community.

eRD29: Precision Timing Silicon Detectors for a Combined PID and Tracking System at the EIC

Wei Li and Friederike Bock reporting

The Committee thanks eRD29 for its presentation and report. The Committee looks with favor on this effort which appears to be well integrated with related efforts for CMS at the HL-LHC. The Committee is also pleased to see the formation and membership in a broader LGAD effort spanning NP and HEP. The Committee is also very aware of the extremely short timescales shown, at the overall EIC project level, for the critical decision process, with CD2 in the very near future. The Committee's recommendations are, to some extent, influenced by this.

Findings

The efforts of this project are well integrated with the related ones in CMS for the HL-LHC. CMS however does not have a barrel timing layer, based upon LGADs, so this is an area where the EIC project will need additional development. The EIC tracking and PID requirements also drive the project to finer segmentation than planned for the HL-LHC. Considerable effort is also aimed at evaluating thin LGADs and this has been delayed due to COVID. Nonetheless there are significant aspects of the CMS infrastructure, i.e. hybrids, modules, and so forth, from which the EIC project can benefit.

Particular emphasis will need to be placed on the development of appropriate front-end electronics to meet the higher granularity and concurrent power density issues.

A full system layout was presented with a variety of performance measures shown, including an extensive discussion of To determination.

Discussion was presented on performance at higher momenta. Some of this was hard to interpret, particularly in relationship to EIC wide requirements and specifications.

Comments

For CMS the need to operate at -30 C requires a complex CO_2 cooling system, which may be not optimal for the EIC. On the other hand, the EIC will be dealing with higher power density. So, this can lead to different optimizations of the cooling system – temperature, coolant, passive materials, and so forth.

Recommendations

The Committee acknowledges that the forward/backward system has the most synergy with CMS and recommends to use, in all cases possible, the same or similar designs for modules, hybrids, and local powering, monitoring, and slow control circuits. Of course, if different segmentation is used, there will be inevitable modifications, but minimize these wherever possible.

Most of our concern is focused on the barrel, which is larger, and has no similar system in CMS. This will require a new and unique design which will differ in many respects from the forward/backward system. Use as much as you can for the latter by certainly deploying resources on the module and integration design in the barrel with urgency. Since you are developing a unique barrel LGAD system, we think the proposed manpower looks thin and we encourage you to expand this effort.

We also note that CMS chose instead LYSO/SiPM for the barrel timing (not tracking). We recommend you confirm that this is not a viable solution for you, schedule and performance wise.

The Committee recommends that you carefully evaluate the requirements for cooling, specific to the EIC and not assume that the -30 C systems at the HL-LHC need to be retained for this environment.

In all cases of LGAD or other fast timing applications, there is a general concern that the performance shown on single devices, under lab test conditions, may not carry over to a full system implementation. To the extent that some of the reported timing resolution numbers are at the edge of the requirements, our concern is increased. We acknowledge a considerable discussion was presented in the report of To determination. We still recommend that the collaboration study further these issues including the effects of combining multiple pads and multiple layers, the effect of segmentation and signal processing, and the integration into a full detector with system timing and clock distribution and calibration issues.

The Committee was concerned with some of the discussion of performance at the higher momenta. There seemed to be differences in specifications between the presentation and the overall detector requirements. We recommend you work more closely with the physics performance coordination team to resolve this.

Appendix: Timelines of the R&D Efforts

The timelines of the major R&D efforts within the larger eRD consortia, as presented at the meeting, are given here in the expectation that they will help the direction of the future research program.

<table>
<tr><th colspan="3">Development of W/SciFi and W/Shashlik Calorimetry for EIC</th></tr>
<tr><th colspan="3">Timeline</th></tr>
<tr><th></th><th>W/SciFi</th><th>W/Shashlik</th></tr>
<tr><th>Year</th><th colspan="2">Tasks</th></tr>
<tr><td>2021</td><td>Continue testing readout options to increase photocathode coverage. Design small prototye (4x4 blocks) to test actual performance. Begin engineering design(s) for actual detector. Barrel and Encap would require completely different designs.</td><td>Design medium size (~ 25 cm2) prototype. Carry out simulations for expected performance. Develop method for making modules projective. Begin engineering design(s) for actual detector. Barrel and Encap would require completely different designs.</td></tr>
<tr><td>2022</td><td>Build small prototype and test in test beam. Continue with engineering design(s) for full scale detector.</td><td rowspan="2">Build prototype(s) and test in test beam.Will likely require at least 2 iterations. Barrel and Endcap would require separate prototypes. Continue with simulations and engineering designs. Design of readout electronics would need to go on in parallel.</td></tr>
<tr><td>2023</td><td>Revise engineering design(s) based on results of prototype tests and design full scale prototype(s).</td></tr>
<tr><td>2024</td><td>Build full scale prototype(s). Test in test beam if possible.</td><td>Revise engineering design(s) based on results of prototype tests. Design full scale prototype(s).</td></tr>
<tr><td>2025</td><td>Complete final design and prepare for construction.</td><td>Build full scale prototype(s). Test in test beam if possible.</td></tr>
<tr><td>2026</td><td></td><td>Complete final design and prepare for construction.</td></tr>
</table>

Table 1: Timeline of the W/SciFi and W/Shashlik efforts within eRD1.

Development of Glass/Crystal for EIC			
Year	PWO	SciGlass	CSGlass `
2021	Complete prototype tests with different readout options	final formulation optimization, scale up to block sizes ≥15 X_0, and establish SciGlass characteristics.	Production of test samples to demonstrate sufficient UV transparency for Cherenkov light collection
2022		Prototype and beam tests. Process design verification to scale up	Composition optimization and initial scale up, establish CSGlass characteristics, e.g. measurements of separation of Cherenkov and Scintillation light of sufficient intensity
2023			Final formulation optimization and scale up to full module size; establish CSGlass characteristics
2024			Prototype and beam tests. Process design verification to scale up
2025			
2026			

Table 2: Timeline of the glass and crystal calorimeter efforts within eRD1.

Timeline-WScFi/FeSc EMC+HCal Prototype Effort	
Year	
2021	Finish optimization of light collection for HCal (WLS/SiPMs) (FY20 fund not received yet) Work out tile catcher integration and frontend electronics for Fe/Sc HCAl Preparation for the construction (need authorization to order long lead time materials) Start construction of 0.6 x 0.6 WScFi + Fe/Sc hadron endcap
2022	Completion of construction of a full scale hadron endcap prototype Beam testing at FNAL in the fall if beam available
2023	More beam testing if needed, Update TDR
2024	
2025	
2026	

Table 3: Timeline of the EM and HCAL prototype efforts within eRD1.

TPC Development for EIC	
Timeline	
Year	**Tasks**
2021	Continue testing readout options (4 GEM vs 2GEM + MMG, zigzag charge sharing, etc) using small scale prototype. Provide input on TPC design for hybrid detector design with TPC and Si inner tracker. In parallel, we also plan to continue to investigate the appllicability of interleaved readout planes for a planar tracker option at EIC.
2022	Design and build prototype hybrid tracker and test in test beam. Continue with engineering design and simulations for full scale detector.
2023	Revise engineering design based on results of prototype tests and design full scale prototype. At this point, depending on the viability of a TPC tracker option at EIC, we will also consider shifting our focus toward MPGD-based planar tracker options with optimized anode geometries.
2024	Build full scale prototype and test in test beam if possible. Revise final design based on prototype tests.
2025	Complete final design and prepare for construction.

Table 4: Timeline of the TPC efforts within eRD6.

Cylindrical MMG Barrel Tracker

Year	Barrel Micromegas Tracker
2021	**Ultra light:** - Goal: from 0.5% X0 (Clas12) to 0.05% X0 with this R&D - Full simulation of ultra light MM design - Design and construction of stretch bulked Kapton demonstrator (no FR4) **2D readout design studies:** - Procurement of large pads readout PCBs - Finalize 2D zigzag readout pattern studies
2022	**Ultra light:** - Aluminium based strips - Thin aluminium mesh manufacturing with laser ablation **Readout studies** - Bulking and test of large pads readout **Cylindrical MM:** - Design of MM tracker support structure within EIC detector
2023	**Ultra light:** - Prototype construction **Cylindrical MM:** - Final prototype with 2D zigzag readout

Table 5: Timeline of the cylindrical micromegas barrel tracker efforts within eRD6.

Cylindrical μRWELL Barrel Tracker

TASK	Development of Cylindrical uRWELL
YEAR	detailed tasks
2021	Completion of mechanical mockup
	Procure components and begin building small-radius functional cylindrical uRWELL
2022	Complete construction of small cylindrical prototype
	Commission small cylindrical prototype
	Perform beam test of small cylindrical prototype
	Analyse beam test results
	Design and procure materials for full-size mechanical mock-up
2023	Finish analyzing beam test results
	Build full-size mechanical mock-up and evaluate
	Design and build large-radius cylindrical uRWELL prototype
2024	Complete large cylindrical uRWELL prototype
	Perform beam test of large cylindrical uRWELL prototype
2025	Complete analysis from large cylindrical uRWLL prototype test beam
	Begin design of production detectors

Table 6: Timeline of μRwell barrel tracker efforts within eRD6.

Planar μRWELL End cap Tracker

TASK	**R&D on Large & low-mass μRWELL for End cap Trackers** 1-) Large & low-mass μRWELL detectors 2-) Development of high performance capacitive-sharing anode readout
YEAR	detailed tasks - **(date are expected milestone)**
2021	**Large μRWELL**
	Dec 2021: Design of large prototype (synergy with prototyping at Jlab)
	Capacitive-sharing readout
	Jun 2021: Study various small prototypes in beam test FNAL
	Dec 2021: Analyse beam test results
	Dec 2021: Optimization & design of large U-V strip capacitive-sharing readout
2022	Jun 2022: construction of large trapezoidal μRWELL with U-V strip readout
	Jul 2022: Test performances of large μRWELL in beam test @ FNAL
	Dec 2022: Analyse beam test results
2023	July 2023: Publication of test beam results on large μRWELL in peer-review paper
	Dec 2023: Complete the R&D on large μRWELL for EIC End Cap Tracker

Table 7: Timeline of μRwell endcap tracker efforts within eRD6.

Large GEM End Cap Tracker

TASK	**R&D on Large & low-mass GEMs for EIC End Cap Trackers** 1 - UVa prototype with U-V strips readout 2 - FIT prototype with carbon Fiber frames & zigzag strip readout
YEAR	detailed tasks - (**date are expected milestone)**
2021	**UVa prototype**
	Jun 2021: Test performance in beam test at FNAL
	Dec 2021: Finalize FNAL test beam data analysis
	FIT prototype
	Jun 2021: Complete the refurbishment & test performance at FNAL
	Dec 2021: Finalize FNAL test beam data analysis
2022	**UVa GEM prototype & FIT GEM prototype**
	Jul 2022: Publication of beam test results in peer-reviewed journal
	Completion of the generic large, low-mass GEM R&D program

Table 8: Timeline of the large GEM chamber endcap tracker efforts within eRD6.

TASK	Development of MPGDs for High Momentum Hadron PID, Development of MPGD sensors of single photons
YEAR	detailed tasks
2021	complete the construction of the prototype version 2
	initial lab test of prototype version 2
	read-out chain based on VMM3 FE fully operational
2022	complete the lab test of prototype version 2
	validate the read-out of single photoelectron signal with VMM3
2023-2024	if sensor selected for the EIC detector, detailed engineering

Table 9: Timeline of the high-momentum MPGD PID efforts within eRD6.

TASK	Development of MPGDs for High Momentum Hadron PID, New Photocathode Materials for gaseous detector
YEAR	detailed tasks
2021	H-ND effective QE in different gas mixutes
	H-ND effective QE after thermal cycle in inert gas
	construction of a complete detector with H-ND photocathodes
	coating substrate sample with CsI for comparative studies
2022	performe the comparative studies of H-ND and CsI
	lab test of the complete detector with H-ND photocathodes
	quantify the radiation hardness of H-ND photocathodes
2023	systematic measurements of QE of H-ND with different grain size
	systematic measurements of QE of H-ND with different graphite content
	systematic measurements of QE of H-ND from different providers
	systematic measurements of QE of H-ND with different B doping
2024	completion of the 2023 exercises

Table 10: Timeline of the MPGD photocathode development efforts within eRD6.

HPDIRC R&D TIMELINE

Mar 2021	hpDIRC Timeline Estimate	2021	2022	2023	2024
			FY22	FY23	FY24
Simulation/Reconstruction	Simulation: Prototype, beam line, cosmic ray setup (CRT)				
	Simulation: Lens characterization				
	Simulation: Explore hpDIRC design options (e/π,π/K)				
	Simulation: Cost/performance optimization				
	Reconstruction: reconstruction optimization / ML				
hpDIRC system prototype	Transfer of PANDA prototype from GSI to CUA/SBU				
	Design and construction of CRT				
	Initial protoype commissioning in cosmic ray setup (CRT)				
	Upgrade of sensors and readout electronics				
	Commissioning of upgraded prototype, CRT data analysis				
	Optional beam test at Fermilab				
	Beam test data analysis				
Lens evaluation	Upgrade of ODU laser setup				
	Characterization of prototype lenses				
	Neutron irradiation and analysis				
BaBar DIRC bar reuse	Plan, preparation				
	Bar box disassembly, bar decoupling				
	Validate mechanical and optical properties				
Sensors and Electronics	collaboration effort within eRD14				
TDR					

Table 11: Timeline of the hpDIRC R&D efforts within eRD14.

MRICH R&D TIMELINE

Mar 2021	mRICH Timeline Estimate	2021	2022	2023	2024
			FY22	FY23	FY24
Beam tests / data analysis	Complete 2nd beam test data taken with SiPM matrices				
	mRICH beam test at JLab with tracking				
	mRICH/LAPPD beam test at Fermilab with tracking				
	JLab and Fermilab beam tests data analysis				
	More beam tests with new photosensors and readout				
mRICH simulation studies	Fine tune GEANT4 simulation of mRICH (2nd prototype)				
	mRICH array simulation study using Fun4All framework				
	Simulation studies of physics impact using mRICH				
	mRICH-based PID algorithm development				
mRICH engineering design	Optimizing the mechanical design of mRICH				
	Optimizing the design and assembly of optical components				
	Optical characterization of aerogel, fresnel lens and mirror				
	Optimizing readout integration with mRICH optical section				
mRICH optical components	Aerogel acquisition (with INFN team) and characterization				
	Fresnel lens acquisition and characterization				
	High quality mirror acquisition and characterization				
Sensors and Electronics	Collaboration effort within eRD14				
TDR					

Table 12: Timeline of the mRICH R&D efforts within eRD14.

dRICH R&D Timeline

Mar 2021	dRICH Timeline Estimate	2021	2022	2023	2024
			FY22	FY23	FY24
Simulation/Reconstruction	Simulation: Prototype and beam line				
	Simulation: Integration into EIC simulation and analysis platforms				
	Simulation: dRICH model refinement with the beam-test results				
	Simulation: dRICH model optimization in EIC spectrometer				
	Reconstruction: reconstruction optimization / ML				
dRICH Prototype	Basic prototype design				
	Basic prototype mechanics				
	Basic tracking and components, reference readout				
	Upgrade of sensors and readout electronics				
	Precise tracking/alignment				
	Custom components, optimized readout				
	Beam test data analysis				
Optical Components	First selection and tests				
	Refinement and cost reduction study				
	Alternatives and optimization				
Beam-Tests	Proof of principle (reference sensors and readout, ideal beam)				
	Performance assessment (hadron tagged beams)				
	Performance assessment with optimized components				
EIC Integration	Cooling R&D				
	EIC configuration engineering and integrated PID				
	Engineering of cooling and ancillary services				
Sensors and Electronics	Collaboration effort within eRD14				
TDR					

Table 13: Timeline of the dRICH R&D efforts within eRD14.

Photosensors R&D Timeline

Mar 2021	Photosensors Timeline Estimate	2021	2022	2023	2024
			FY22	FY23	FY24
High-B Sensor Program	Scan of 10-µm XP85122-S, HiCE Planacon				
	Scan of 6-µm Photek MCP PMT, MAPMT253				
	Full-area uniformity scan with UHawaii electronics				
	Incom GEN-III (HRPPD) scan				
MCP-PMT/LAPPD	Beamline test of MCP-PMT/LAPPD with pixel readout				
	mRICH-LAPPD-ToF experiment with Gen-II LAPPD				
	Magnetic field test of LAPPD prototypes				
	Fabrication of 10x10 cm MCP-PMT for prototype validation				
	Bench evaluation of MCP-PMT, LAPPD and HRPPD				
	Integration of UHawaii electronics with available sensors				
	Beamline evaluation of RICH subsystems with available MCP-PMT/ LAPPD				
SiPM program	Status-of-the-art sensor selection				
	Irradiation and temperature treatment (standard sensors)				
	Post-irradiation response with dedicated readout				
	Custom sensor solutions (with manufacturers)				
	Irradiation and temperature treatment (custom sensors)				
	Engineering of cooling and services				
Sensors and Electronics	Collaboration effort within eRD14				
TDR					

Table 14: Timeline of the photosensor R&D efforts within eRD14.

Year	Detailed tasks
2021	• Testing and characterization of MLR1 • Sensor design for MLR2 • MLR2 submission • R&D into powering, stave/disc construction, cooling, overall infrastructure
2022	• Testing and characterization of MLR2 • Sensor design for ITS3 ER1 • ITS3 ER1 submission • R&D + prototyping into powering, stave/disc construction, cooling, overall infrastructure
2023	• Testing and characterization of ITS3 ER1 and assessment of yield • Assessment and planning for EIC sensor fork of ITS3 design • Fork off sensor design and work on EIC variant for staves and discs (may move to next year depending on results) • ER submission for EIC variant sensor (EIC ER1) for staves and discs • Detailed prototyping into powering, stave/disc construction, cooling, overall infrastructure • Investigation of adaptation of ITS3 design for use in EIC vertex layers (different radii, # layers, services from both ends to meet length requirements, etc.) with ITS ER1
2024	• Testing and characterization of EIC ER1 and assessment of yield • Si design for EIC ER2 • EIC ER2 submission for EIC variant sensor for staves and discs • Detailed prototyping into powering, stave/disc construction, cooling, overall infrastructure using EIC ER1 prototypes • Adaptation of ITS3 design for use in EIC inner layers with ITS2 ER2 (or integration of design into EIC ER2 if necessary).
2025	• Testing and characterization of EIC ER2 and assessment of yield • Complete stave and disks prototypes with EIC ER2 • Vertex layers prototypes with ITS2 ER3

Table 15: Timeline of the silicon sensor and tracking efforts within eRD25.